Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR–2001/02 June 2001

Survivability, Structures, and Materials Directorate

Technical Report

Investigation of Submerged Arc Welding with Improved MIL-100S Wires (LC-100)

by

G. L. Franke

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-06-2001

2. REPORT TYPE
Research and Development

3. DATES COVERED *(From - To)*
-

4. TITLE AND SUBTITLE
Investigation of Submerged Arc Welding with Improved MIL-100S Wires (LC-100)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
G. L. Franke

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
1-6150-754

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
NAVAL SURFACE WARFARE CENTER
CARDEROCK DIVISION (CODE 615)
9500 MACARTHUR BOULEVARD
WEST BETHESDA, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-61-TR-2001/02

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ATTN CODE 332
CHIEF OF NAVAL RESEARCH
BALLSTON CENTRE TOWER ONE
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Navy is conducting a program to develop and certify an improved MIL-100S wire for welding HSLA and HY steels. The goal of the effort is to produce a welding wire with better hydrogen cracking resistance than the current MIL-100S wire, enabling HSLA-80 and HSLA-100 steels to be fabricated without preheat (60° F minimum) for plate thicknesses up to two inches. A Navy, industry, and academic development effort produced and evaluated a number of experimental low-carbon welding consumables. Gas metal arc weldments produced with these wires demonstrated increased hydrogen cracking resistance compared to current MIL-100S wires, while maintaining acceptable weld metal strength and toughness over a wide range of weld metal cooling rate conditions. In the present study, limited submerged arc welding characterization of these wires was conducted to determine if any flux or wire modifications would be required to permit their use in submerged arc welding applications. Weldments were produced with one commercial flux and the three 0.045-inch-diameter experimental wires, as well as 0.045-inch-diameter and 0.093-inch-diameter sizes of one current heat of MIL-100S wire. Three other commercial fluxes were used to produce additional weldments with the 0.093-inch-diameter MIL-100S wire. All weldments were produced in one-inch-thick HSLA-100 steel at a calculated cooling rate of approximately 35° F/s. Weld metal properties were tested to determine adequacy of the experimental wires for submerged arc welding, for comparison to current MIL-100S wires in SAW, and performance variations due to wire size and flux composition variations. The results indicated that the experimental wires exhibited acceptable strength and toughness, wire size scale up should not adversely affect properties, and use of other commercial fluxes with these wires should not generally be a problem. Based on these results no modifications to the wire or the fluxes were deemed necessary.

15. SUBJECT TERMS
HSLA steels   Submerged arc welding   Welding consumables   Weld metal

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Gene L. Franke
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	36	19b. TELEPHONE NUMBER *(include area code)* 301-227-5571

Contents

Tables

Figures

Abstract

The Navy is conducting a program to develop and certify an improved MIL-100S wire for welding HSLA and HY steels. The goal of the effort is to produce a welding wire with better hydrogen cracking resistance than the current MIL-100S wire, enabling HSLA-80 and HSLA-100 steels to be fabricated without preheat (60°F minimum) for plate thicknesses up to two inches. A Navy, industry, and academic development effort produced and evaluated a number of experimental low-carbon welding consumables. Gas metal arc weldments produced with these wires demonstrated increased hydrogen cracking resistance compared to current MIL-100S wires, while maintaining acceptable weld metal strength and toughness over a wide range of weld metal cooling rate conditions. In the present study, limited submerged arc welding characterization of these wires was conducted to determine if any flux or wire modifications would be required to permit their use in submerged arc welding applications. Weldments were produced with one commercial flux and the three 0.045-inch-diameter experimental wires, as well as 0.045-inch-diameter and 0.093-inch-diameter sizes of one current heat of MIL-100S-1 wire. Three other commercial fluxes were used to produce additional weldments with the 0.093-inch-diameter MIL-100S-1 wire. All weldments were produced in one-inch-thick HSLA-100 steel at a calculated cooling rate of approximately 35°F/s. Weld metal properties were tested to determine adequacy of the experimental wires for submerged arc welding, for comparison to current MIL-100S wires in SAW, and performance variations due to wire size and flux composition variations. The results indicated that the experimental wires exhibited acceptable strength and toughness, wire size scale up should not adversely affect properties, and use of other commercial fluxes with these wires should not generally be a problem. The experimental wires were also superior to the comparable MIL-100S-1 wire (0.045 inch diameter) in SAW weld metal tensile and impact performance. Based on these results no modifications to the wire or the fluxes were deemed necessary.

Acknowledgments

All weldments in this study were produced by Mr. R. Benzel, formerly of Code 615. Messrs. J. Blackburn, J. DeLoach, and R. Wong provided input to the analysis.

Administrative Information

This report was prepared as part of the Welding Technologies Task of the ONR 6.2 Seaborne Structural Materials Program, Subtask on LCB Consumables for Flux-Assisted

Welding Processes. The program sponsor is Dr. George Yoder, Office of Naval Research (ONR 332). The technical agent is Mr. Charles Null, Naval Sea Systems Command (SEA 05M2). This effort was supervised by Messrs. R. DeNale and J. DeLoach, Naval Surface Warfare Center, Carderock Division (NSWCCD 61 and 615).

Introduction

High strength HSLA steel plate has been used in U.S. Navy ship construction since 1985. These steels are more resistant to heat affected zone cracking than the HY steels they replaced, permitting the reduction of welding preheats. However, the welding consumables available for these steels are still those designed for the HY steels, and their weld metals are still susceptible to hydrogen cracking. This cracking susceptibility requires the continued use of welding preheats for certain applications, and the full potential benefits of the HSLA steels cannot yet be realized. To address this shortcoming, the Navy is conducting a program to develop and certify improved MIL-100S wire (nominal 80 ksi minimum yield strength) for welding HSLA and HY steels. The goal of this effort is to produce a welding wire with better hydrogen cracking resistance than the existing MIL-100S wires, enabling HSLA-80 and HSLA-100 steels to be fabricated without preheat (60° F minimum) for plate thicknesses up to two inches. Minimum preheat requirements for current MIL-100S wires are as high as 125° F to 200° F, depending on the application and thickness of plate being welded [1]. The wire must also produce acceptable welds in HY-80 and HY-100 steels. The operational and mechanical property goals for the improved MIL-100S wire are presented in Table 1 [2]. The weld metal cooling rate conditions listed in the table are based on calculations of cooling rates in gas metal arc welding established in the literature [3-5].

Navy, industry, and academic development efforts have produced and evaluated a number of experimental low-carbon (LC) welding consumables. Gas metal arc weldments produced with these wires have demonstrated increased resistance to hydrogen cracking compared to the current MIL-100S wires, while still maintaining acceptable weld metal strength and toughness over a wide range of weld metal cooling rates [6].

A viable MIL-100S product for Navy shipbuilding should also be acceptable for SAW. Thus, prior to the selection of a candidate wire composition for a prototype production heat, it was decided to conduct a limited evaluation of these new wires in submerged arc welding (SAW) applications. Any modifications to the wire or flux compositions to permit use of the

Table 1. Operational and mechanical property targets for improved MIL-100S weld metal.

Base Metal	Minimum Preheat/Interpass Temperature (°F)	Calculated Weld Metal Cooling Rate at 1000° F (° F/s)	Yield Strength (ksi)	Charpy V-Notch Energy (ft-lb)	5/8" Dynamic Tear Energy (ft-lb)
HSLA-80 HY-80	60	5 – 100	82 - 120	35 at -60° F 60 at 0° F	300 at -20° F 450 at 30° F
HSLA-100 HY-100	60	12 - 100	88 - 120	35 at -60° F 60 at 0° F	300 at -20° F 450 at 30° F

wire for SAW would be determined here. Following characterization of the experimental alloys by gas metal arc welding, limited submerged arc welding characterization was conducted with the candidate LC-100 alloys.

Objective

The objective of this investigation was to conduct a limited characterization of the mechanical property performance of the experimental LC-100 wires in submerged arc welding and determine if any flux or wire modifications would be required to permit their use in submerged arc welding applications.

Materials

Small quantities of three candidate experimental LC-100 wires were evaluated in this study. These experimental wires were identified as Alloys 1, 2, and 4. They were only available as 0.045-inch diameter wires. The compositions of the experimental wires and their target compositions are shown in Table 2. Specific levels for carbon, manganese, silicon, nickel, and molybdenum were targeted for each alloy. In addition, chromium was to be minimized. Except for carbon, target compositions were achieved for all three wires. Carbon in the three wires was higher than the target by approximately 0.01 wt%. It was also noted that nitrogen levels in the wires were held below 10 ppm.

A heat of current MIL-100S-1 wire, in both 0.045-inch and 0.093-inch diameters, was also used to produce weldments for mechanical property and size effect comparisons with the three experimental wires. The compositions of the MIL-100S-1 wires are presented in Table 3. Both wire sizes met specification requirements [7], however, carbon in the larger wire was approximately 0.01% higher than in the small wire. This difference in carbon between the two

Table 2. Chemical composition of experimental welding wires used for submerged arc weldments (wt%).

Element	Alloy 1 Ht D55630 0.045 in.	Alloy 1 Target Composition [2]	Alloy 2 Ht D55627 0.045 in.	Alloy 2 Target Composition [2]	Alloy 4 Ht D55629 0.045 in.	Alloy 4 Target Composition [2]
C	0.034	0.025	0.035	0.025	0.036	0.025
Mn	1.74	1.7	1.90	1.9	1.64	1.7
Si	0.36	0.35	0.36	0.35	0.35	0.35
S	0.003		0.001		< 0.001	
P	< 0.002		0.002		< 0.002	
Ni	2.58	2.6	2.55	2.6	2.91	3.0
Mo	0.60	0.6	0.59	0.6	0.59	0.6
Cr	0.001	--	0.004	--	< 0.001	--
Cu	< 0.001		< 0.001		< 0.001	
Ti	0.012	0.015	0.007	0.015	0.013	0.015
Al	0.002		0.002		0.002	
Nb	0.001		0.003		0.004	
V	< 0.002		< 0.002		< 0.002	
Zr	< 0.001		< 0.001		< 0.001	
B	0.004		0.004		0.004	
O*	57		69		64	
N*	5		6		9	
H*	4		6		8	

* Values are in ppm.

wires may be due to the additional processing required to draw the wire down to 0.045 in., or it may just be indicative of the variation of carbon within the heat of steel. Comparison of Tables 2 and 3 clearly shows the design differences between the MIL-100S-1 and experimental LC-100 wires for carbon, nickel, molybdenum, and chromium. In addition, the nitrogen content of the MIL-100S-1 wires was about 20 times higher than that of the LC-100 wires and the boron level in the experimental wires was about 10 times higher than that in the MIL-100S-1 wires.

One-inch-thick HSLA-100 steel, produced to specification requirements [8], and identified as Tag 423, was the base plate used for all weldments produced in this investigation. The chemical composition of this plate is presented in Table 3.

Four different submerged arc welding fluxes of interest to the Navy, manufactured by three different consumables producers, were used to produce the weldments. Typical flux compositions, based on comprehensive analyses, are presented in Table 4. In addition, fluxes C and D were known to employ some means of weld metal hydrogen management.

Table 3. Chemical composition of current welding wire and plate used for submerged arc weldments (wt%).

Element	MIL-100S-1 Ht 095222 0.045 in.	MIL-100S-1 Ht 095222 0.093 in.	Wire Specification [7]	HSLA-100 Tag 423 1 in.	Plate Specification [8]
C	0.051	0.062	0.08 max	0.059	0.06 max
Mn	1.73	1.69	1.25 – 1.80	1.07	0.75 – 1.15
Si	0.31	0.40	0.20 – 0.55	0.28	0.40 max
S	0.006	0.007	0.01 max	0.006	0.06 max
P	0.006	0.009	0.01 max	0.012	0.020 max
Ni	1.78	1.79	1.40 – 2.10	1.65	1.50 – 2.00
Mo	0.33	0.32	0.25 – 0.55	0.38	0.30 - 0.55
Cr	0.094	0.097	0.30 max	0.63	0.45 – 0.75
Cu	0.015	0.018	--	1.17	1.00 – 1.30
Ti	0.013	0.013	0.10 max	0.006	0.02 max
Al	0.007	0.003	0.10 max	0.027	0.015 min
Nb	0.002	0.004	--	0.036	0.02 – 0.06
V	0.007	0.007	0.05 max	0.004	0.03 max
Zr	0.004	0.004	0.10 max	0.003	--
B	0.0005	< 0.0005	--	0.0009	--
O*	69	35	--	31	--
N*	120	110	--	60	--
H*	3.3	1.6	--	1.2	--

* Values are in ppm.

Table 4. Typical compositions of fluxes used for submerged arc weldments (wt%).

Compound	Flux A	Flux B	Flux C	Flux D
Al_2O_3	18.2	15.4	16.2	13.1
CaF_2	22.2	20.9	23.4	14.0
CaO	10.2	9.9	6.9	17.3
K_2O	0.99	1.34	1.02	1.24
MgO	28.9	32.1	33.2	28.3
MnO	0.99	2.10	1.55	0.08
Na_2O	0.94	1.20	1.16	1.99
SiO_2	14.7	14.5	13.7	16.5
TiO_2	0.72	0.52	0.45	ND*
REO*	0.015	0.018	0.008	0.691
LOI*	1.41	0.80	2.20	4.97
BI*	2.70	3.05	3.04	2.78

* REO = Rare Earth (Ce, La, Nd, Y) Oxides
LOI = Loss on Ignition at 925 °F
BI = Basicity Index (dimensionless) [9]
ND = Not Detected

Procedure

Eight weldments were produced in one-inch-thick HSLA-100 steel plate. The combinations of the wires, wire sizes, and fluxes are listed in Table 5. The desire was to characterize the performance of the experimental LC-100 wires when used with a number of submerged arc welding fluxes of interest to the Navy. Due to the small quantities of these wires available for use, the MIL-100S-1 wires were used to study the effects of the different fluxes and the effects of wire size differences. The effects witnessed with the MIL-100S-1 wires were then extrapolated to the experimental wires.

Three weldments were produced with each of the experimental wires and flux A. The remaining five weldments were produced with the MIL-100S-1 wires. One of these MIL-100S-1 weldments was produced with the 0.045-inch-diameter wire and flux A to directly compare the performance of the experimental wires to that of the existing MIL-100S-1 wire. The remaining MIL-100S-1 weldments were produced with the 0.093-inch-diameter wire and the four different SAW fluxes. In this way, wire size effects and flux composition effects could be compared.

A nominal mid-range heat input of 45 kJ/in was used for all weldments. The single-vee joint design is shown in Figure 1. The backing bar was 0.5-inch-thick HSLA-100. Welding conditions for all weldments are presented in Table 5. Thermocouples were plunged in the weld pool of each bead of the MIL-100S-1 weldments to obtain weld metal cooling rate data.

Completed weldments were radiographed for soundness, and sectioned for mechanical property specimen machining and testing. All-weld-metal 0.505-inch-diameter tensile specimens were tested at room temperature. Charpy V-notch (CVN) specimens were tested at temperatures ranging from -240° F to 240° F to obtain full CVN transition curves. Weld metal chemistry was determined from the reduced section of a tested tensile specimen from each weldment.

Test results for the experimental wires were compared to the program targets for improved MIL-100S wires presented in Table 1, specification requirements for current MIL-100S wires [10], and results from the MIL-100S-1 weldments.

Table 5. Welding conditions for submerged arc weldments.

Weld I.D.	Wire	Wire Size (in.)	Flux	Weld Length (in.)	Voltage (V)	Current (A)	Travel Speed (ipm)	Heat Input (kJ/in)	Preheat/ Interpass Temperature (° F)
F-391	MIL-100S-1	0.093	A	48	35	500	23	45.7	125 - 150
F-392	MIL-100S-1	0.093	B	48	35	500	23	45.7	125 - 150
F-393	MIL-100S-1	0.093	C	48	35	500	23	45.7	125 - 150
F-394	MIL-100S-1	0.093	D	48	35	500	23	45.7	125 - 150
F-395	MIL-100S-1	0.045	A	48	34	200	9	45.3	125 - 150
F-396	Alloy 1	0.045	A	36	34	200	9	45.3	125 - 150
F-397	Alloy 2	0.045	A	36	34	200	9	45.3	125 - 150
F-399	Alloy 4	0.045	A	36	34	200	9	45.3	125 - 150

Results

Weld Metal Cooling Rates

Weld metal cooling rates for each weld bead were calculated using expressions established specifically for SAW [11] and the parameters recorded during welding. Weld metal cooling rates were also measured using thermocouple plunges made in the MIL-100S-1 weldments. Average calculated and measured cooling rates are compared in Table 6. The measured cooling rate values consistently range from 10° F/s to 15° F/s lower than the calculated cooling rates. While calculated cooling rates have been used for weld metal characterization in the LC-100 program, measured values should be considered more accurate. There may be a number of differences between the conditions under which the SAW cooling rate expression was derived and those of this investigation that would account for the differences. Such differences have been discussed previously [12]. Regardless of which set of cooling rates are considered, both fall within the range of operational targets for the improved wire.

Weld Metal Chemistry

The weld metal chemistry results are presented in Table 7. Differences in carbon, nickel, molybdenum, and chromium noted earlier between the experimental wires and the MIL-100S-1 wires have carried into the weld metals. Manganese was lost in all cases. Differences in carbon, molybdenum, chromium, and boron, noted earlier, are still discernable. In addition, high weld metal oxygen contents reflect the influence of the fluxes used in the SAW process.

Table 6. Cooling rate conditions for submerged arc weldments.

Weldment I.D.	Wire	Wire Size (in.)	Flux	Average Calculated C.R.* (°F/s)	Average Measured C.R.* (°F/s)	Number of Beads
F-391	MIL-100S-1	0.093	A	35.8	25.4	19
F-392	MIL-100S-1	0.093	B	35.7	23.9	22
F-393	MIL-100S-1	0.093	C	36.0	25.9	23
F-394	MIL-100S-1	0.093	D	35.5	23.7	23
F-395	MIL-100S-1	0.045	A	36.2	21.6	18
F-396	Alloy 1	0.045	A	35.9	ND**	17
F-397	Alloy 2	0.045	A	36.0	ND**	17
F-399	Alloy 4	0.045	A	35.8	ND**	17

* C.R. = Cooling Rate at 1000° F

** ND = Not Determined

Table 7. Weld metal chemistry for submerged arc weldments (wt%).

Element	F391	F392	F393	F394	F395	F396	F397	F399
Wire	MIL-100S-1					Alloy 1	Alloy 2	Alloy 4
Size	0.093 in.				0.045 in.	0.045 in.		
Flux	A	B	C	D	A	A		
C	0.049	0.044	0.062	0.047	0.037	0.024	0.028	0.028
Mn	1.42	1.35	1.42	1.42	1.46	1.47	1.63	1.47
Si	0.31	0.27	0.27	0.38	0.29	0.39	0.39	0.38
S	0.004	0.004	0.004	0.006	0.004	0.002	0.003	0.001
P	0.012	0.008	0.008	0.009	0.012	0.004	0.005	0.006
Ni	1.78	1.67	1.77	1.70	1.67	2.62	2.62	2.94
Mo	0.32	0.30	0.33	0.31	0.30	0.59	0.59	0.60
Cr	0.16	0.14	0.24	0.13	0.096	0.012	0.018	0.019
Cu	0.21	0.16	0.39	0.12	0.065	0.029	0.039	0.034
Ti	0.008	0.003	0.004	0.003	0.004	0.006	0.004	0.005
Al	0.013	0.010	0.013	0.011	0.010	0.011	0.011	0.011
Nb	0.010	0.007	0.012	0.006	0.004	0.010	0.011	0.010
V	0.005	0.006	0.004	0.004	0.006	0.002	0.002	0.002
Zr	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
B	<0.0005	0.0005	<0.0005	0.002	<0.0005	0.004	0.005	0.003
O*	380	390	390	410	350	310	310	300
N*	120	120	110	110	120	9	9	8
H*	1.4	1.1	1.3	1.4	1.8	1.0	1.4	1.0
P_{CM}	0.203	0.186	0.228	0.203	0.179	0.216	0.234	0.221

* Values are in ppm.

P_{CM} values were calculated using eqn. 1 [13], and are included in Table 7. It is interesting to note the difference in P_{CM} between F391 and F395, weldments produced with the same flux, but different sizes of the same heat of MIL-100S-1 wire. The lower carbon of F395 follows from the wire chemistry. Differences in nickel, chromium, and copper must stem from the welding process. However, it is not clear whether these chemistry differences are due to the size of the wire used for each weldment or some other factor during welding. Interestingly, the weld copper values for all the small-diameter-wire welds are similar in magnitude and lower than those for the large-diameter-wire welds.

$$P_{CM} = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B \qquad \text{eqn 1}$$

Tensile Properties

Tensile test results for the eight submerged arc weldments are presented in Table 8 and are compared to specification requirements [7] for the MIL-100S-1 wire used and LC-100 program targets [2], which are the same as current MIL-100S-1 specification requirements [10]. All weldments met both sets of tensile requirements. The weldments produced with the three experimental wires exhibited yield strengths from 94 to 99 ksi with good elongation. Yield strengths for the MIL-100S-1 weldments ranged from 91 to 108 ksi depending on the wire size and flux used.

There is a definite strength difference between the MIL-100S-1 welds produced with wires of different size. Strength of the larger-diameter-wire weld metal was higher than for the smaller wire, and the ductility measures of elongation and reduction of area were lower. These differences can be explained by the variation in P_{CM} for the two weld metals.

Tensile values increase with increasing P_{CM}, but this trend is shifted to higher P_{CM} values for the three LC-100 wires (*i.e.*, their tensile properties are lower than the MIL-100S-1 wires for similar P_{CM} values). This trend is shown in Figure 2a. The significant increase in nitrogen content of the MIL-100S-1 weld metals compared to the LC-100 weld metals also plays an important part in their higher strength levels for similar P_{CM} values.

The differences in the MIL-100S-1 weldments, at least for those 0.093 in. in diameter, derive from the use of the different fluxes, since welding conditions were held constant. If, however, these trends are plotted for wire size rather than alloy type, definite bands are observed, as shown in Figure 2b. This figure indicates that strength differences are due to wire size effects.

Table 8. Tensile properties of submerged arc weldments.

Weldment I.D.	Wire	Wire Size (in.)	Flux	0.2% Offset Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)	Reduction of Area (%)
F391	MIL-100S-1	0.093	A	99 100	108 108	21 21	64 64
F392	MIL-100S-1	0.093	B	97 97	104 104	24 25	67 68
F393	MIL-100S-1	0.093	C	101 108	110 109	22 25	64 70
F394	MIL-100S-1	0.093	D	98 99	104 105	23 23	69 69
F395	MIL-100S-1	0.045	A	91 92	98 98	26 26	70 71
Specification Requirements [7]				82 - 110	*	16 minimum	*
F396	Alloy 1	0.045	A	96 94	104 102	25 25	71 71
F397	Alloy 2	0.045	A	98 99	105 105	26 24	71 72
F399	Alloy 4	0.045	A	96 98	104 105	24 24	70 69
Tensile Property Targets [2, 10]				82 - 120	--	16 minimum	--

* - For information only.

It is possible that the difference in welding parameters between the two wire sizes (see Table 5) resulted in different bead shape and size, penetration, dilution (*e.g.*, note Cu differences for the two wire sizes), reheating, and other characteristics of the weld metals, resulting in the two distinct strength bands in Figure 2b.

Impact Properties

CVN data are presented in Tables 9 and 10 for the MIL-100S-1 and experimental LC-100 wires, respectively. The full CVN transition curves for each weldment are presented in the Appendix. From these figures, the fracture appearance transition temperatures (FATT) presented in Table 11 were determined. The weldments for the three experimental LC-100 wires exhibited satisfactory CVN performance compared to the target values, although the values at -60° F varied over a large range. The weldments produced with the MIL-100S-1 wire also met required minimum average impact values, but F394 had three CVN values below 35 ft-lb at -60° F, which would fail additional specification requirements. F394 also had the highest level of oxygen.

Table 9. Charpy V-notch impact energies (in ft-lb) for submerged arc weldments produced with MIL-100S-1 electrodes, and related shear fracture (in percent, in brackets).

Weldment I.D.	-240°F	-180°F	-120°F	-60°F	0°F	30°F	60°F	90°F	120°F	150°F	180°F	240°F
F391 MIL-100S-1 0.093 in. Flux A	4[10]	10[10]	29[40] 46[50] 53[50]	64[30] 69[70] 83[60] 83[70] 100[40]	103[90] 103[80] 106[80] 108[90] 109[90]	--	100[99] 105[99] 108[100] 110[95] 116[99]	--	113[100] 128[100]	--	120[100]	125[100]
F392 MIL-100S-1 0.093 in. Flux B	5[10]	7[10]	7[40] 35[40]	54[50] 59[60] 59[50] 67[60] 70[60]	84[70] 84[70] 91[60] 94[70] 116[70]	--	106[80] 114[80] 141[100]	125[95] 127[95]	132[99] 134[100]	--	128[100] 140[100]	126[100]
F393 MIL-100S-1 0.093 in. Flux C	--	10[10]	19[30] 19[30]	39[50] 41[40] 61[50] 64[50] 76[70]	82[60] 88[80] 93[80] 95[80] 106[70]	--	101[95] 106[100] 120[95]	117[95] 126[95]	125[100] 128[100] 130[95]	115[98] 135[100]	--	142[100]
F394 MIL-100S-1 0.093 in. Flux D	--	7[10]	14[20] 15[30]	25[30] 28[30] 31[30] 53[40] 74[50]	74[60] 90[60] 90[60] 104[70] 105[70]	--	86[70] 106[80] 112[90] 118[80]	--	125[90] 133[95]	130[98] 138[100]	140[100]	137[100] 142[100]
F395 MIL-100S-1 0.045 in. Flux A	4[5]	4[5]	10[10] 14[20] 20[10]	43[30] 45[30] 57[40] 71[70] 83[50]	67[40] 91[60] 98[60] 100[70] 110[80]	90[90] 103[80] 104[80]	113[90] 119[80] 120[90]	--	113[100] 121[100]	--	--	119[100]
Specification Requirement [7]	--	--	--	35* min avg	60* min avg	--	--	--	--	--	--	--

* - No two individual values may be below the minimum average.

Table 10. Charpy V-notch impact energies (in ft-lb) for submerged arc weldments produced with experimental alloy electrodes, and related shear fracture (in percent, in brackets).

Weldment I.D.	-180°F	-120°F	-90°F	-60°F	-30°F	0°F	60°F	120°F	180°F
F396 Alloy 1 0.045 in. Flux A	16[20]	21[20] 32[20]	38[40] 60[40] 62[50]	31[40] 61[50] 62[60] 68[50] 95[80]	94[80] 103[90]	106[80] 107[90] 109[90] 112[80] 122[90]	117[98] 124[90] 130[95]	121[98] 136[100]	124[100]
F397 Alloy 2 0.045 in. Flux A	9[10]	16[20] 20[30]	48[60] 49[50] 83[50]	62[60] 73[50] 88[60] 104[70] 106[80]	103[60] 108[70]	114[90] 116[90] 128[90] 132[95] 132[95]	119[95] 132[100] 134[100]	132[99] 152[100]	132[100]
F399 Alloy 4 0.045 in. Flux A	14[20]	20[30] 26[40]	57[40] 88[50] 92[70]	40[50] 86[70] 96[80] 101[90] 106[80]	107[80] 127[80]	111[90] 119[95] 120[90] 122[90] 128[90]	123[95] 126[98] 140[95]	133[100] 143[100]	136[100]
CVN Targets [2, 10]	--	--	--	35*	--	60*	--	--	--

* - No two values may be below the target value.

Table 11. Fracture appearance transition temperatures for submerged arc weldments.

Weldment	F391	F392	F393	F394	F395	F396	F397	F399
Wire	MIL-100S-1					Alloy 1	Alloy 2	Alloy 4
Size	0.093 in.				0.045 in.			
Flux	A	B	C	D	A			
FATT (° F)	-96	-63	-68	-30	-48	-77	-88	-94

Discussion

One of the goals in this investigation was to determine how the performance of the LC-100 wires compared to that of existing MIL-100S wires. This comparison is shown in Figure 3 for the CVN performance of the three alloy wires and the 0.045-in.-diameter MIL-100S-1 wire. The CVN curves of all three LC-100 wires are to the left of the MIL-100S-1 CVN curve, indicating their lower transition temperature. Higher upper shelf energies are also noted for the alloy wires.

Another goal was to determine how the test results for the small-diameter experimental wires will translate when scaled up to the larger wire sizes normally used for SAW (0.093 in. diameter and larger). This trend is shown in Figure 4 for the two sizes of the current MIL-100S-1 wire used in this investigation. The larger wire shows a better CVN transition temperature while exhibiting equivalent upper shelf energy. The curve is shifted about 50° F lower than the smaller wire. The difference in carbon between the two wire sizes did not affect upper shelf energy. Strength of the larger-diameter-wire weld metal was definitely higher than for the smaller wire and the ductility measures of elongation and reduction of area are lower. Overall, however, this data indicates that there should not be a problem with the scale up of any of these experimental wires with regard to mechanical property performance.

Finally, the performance of the MIL-100S-1 wire was examined for the effects of using different fluxes to produce the weldments. Figure 5 shows the comparison of the weldments produced with the larger MIL-100S-1 wire and the four different fluxes investigated. The best overall performance was evidenced for flux A. The other weld metals exhibited higher upper shelf energies, but their transition temperatures were from 28° F to 66° F higher than that for flux A. Fluxes A, B, and C met the CVN specification requirement at -60° F and 0° F. The flux D weld metal, which had an average CVN value at -60° F exceeding 42 ft-lb, did not meet the -60° F requirement, because three of the five individual CVN energy values at that temperature were below the minimum average value of 35 ft-lb. As noted in Table 9, the specification requires that no more than one value may be below the minimum average value for a given test temperature. It is noted that the flux D weld metal had the highest weld metal oxygen level and exhibited the highest FATT.

Examining the trends in the MIL-100S-1 welds and using the smaller-diameter wire weldment as a baseline, scaling up the size and using the various fluxes had a variety of effects. Flux A increased CVN values at -60° F by 20 ft-lb, flux B slightly increased performance, flux C slightly decreased performance, and flux D reduced performance more than 17 ft-lb. If these same trends are applied to the three alloy wires, the worst performance would be by a larger Alloy 1 wire welded with flux D, resulting in CVN performance of about 45 ft-lb at -60° F, which is still acceptable performance. This is an unlikely scenario, however, since only one of the alloys will be selected for production, and it will likely be Alloy 2 or Alloy 4, based in part on their performance in this investigation. Even the reduction in performance that flux D would impose on these two wires would still presumably result in acceptable CVN performance.

Conclusions

Based on the work described here, a number of conclusions can be drawn. The three experimental LC-100 wires can produce acceptable SAW weld metal mechanical properties when used with flux A. The experimental wires were also superior to the comparable MIL-100S-1 wire (0.045 inch diameter) in SAW weld metal tensile and impact performance. The scale up of any of these wires to standard sizes more suitable for SAW should also result in acceptable performance. It is predicted that they will also exhibit satisfactory performance when welded with the other fluxes used in this work. Based on this work, no modifications of the wires or fluxes are deemed necessary prior to the procurement of the prototype production heat of one of these compositions for full characterization and certification for Navy use.

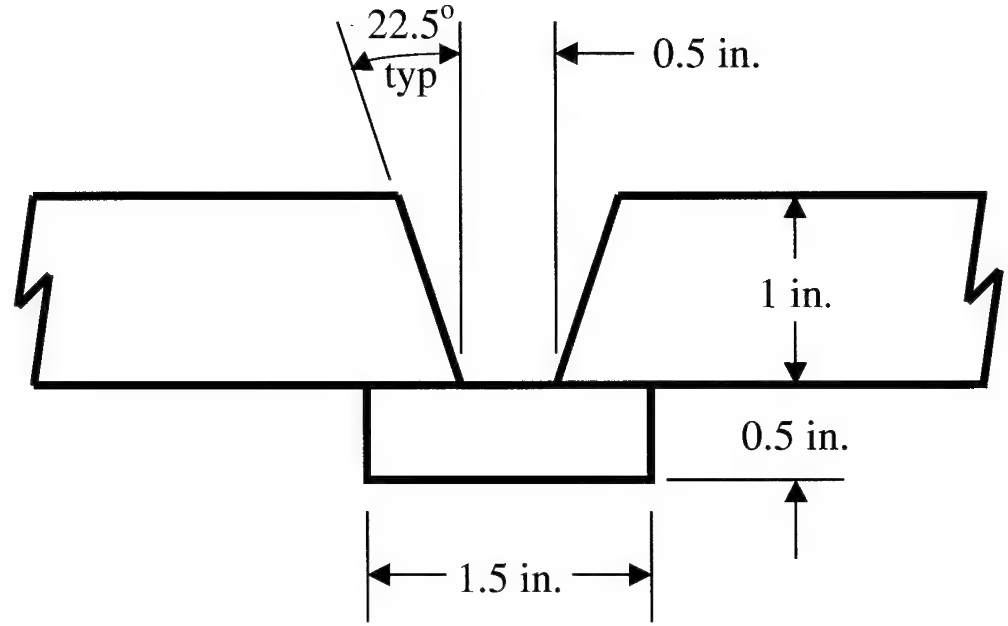

Figure 1. B1V.1 Joint Design Used for Submerged Arc Weldments.

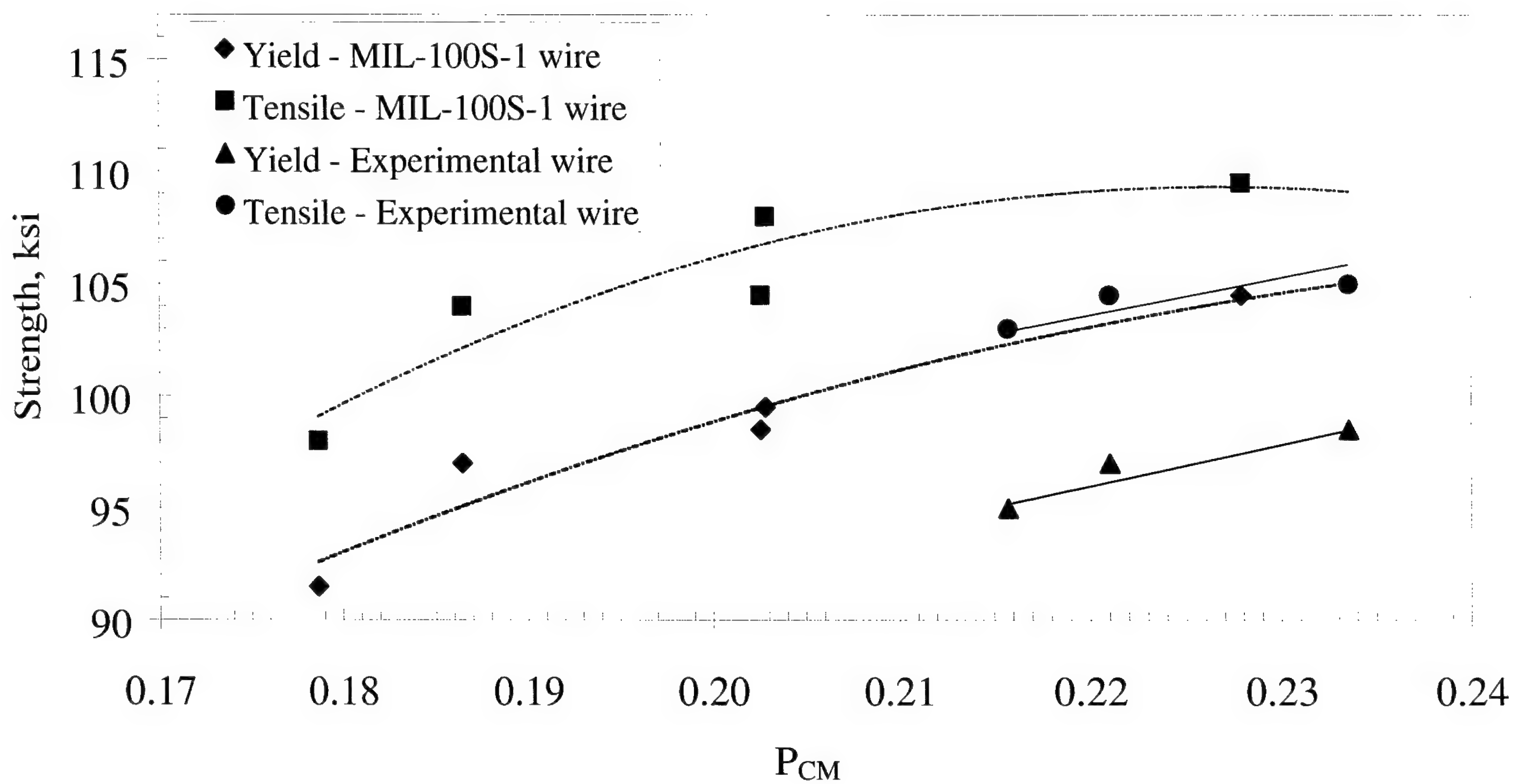

Figure 2a. Weld Metal Strength as a Function of Weld Metal P_{CM} and Alloy.

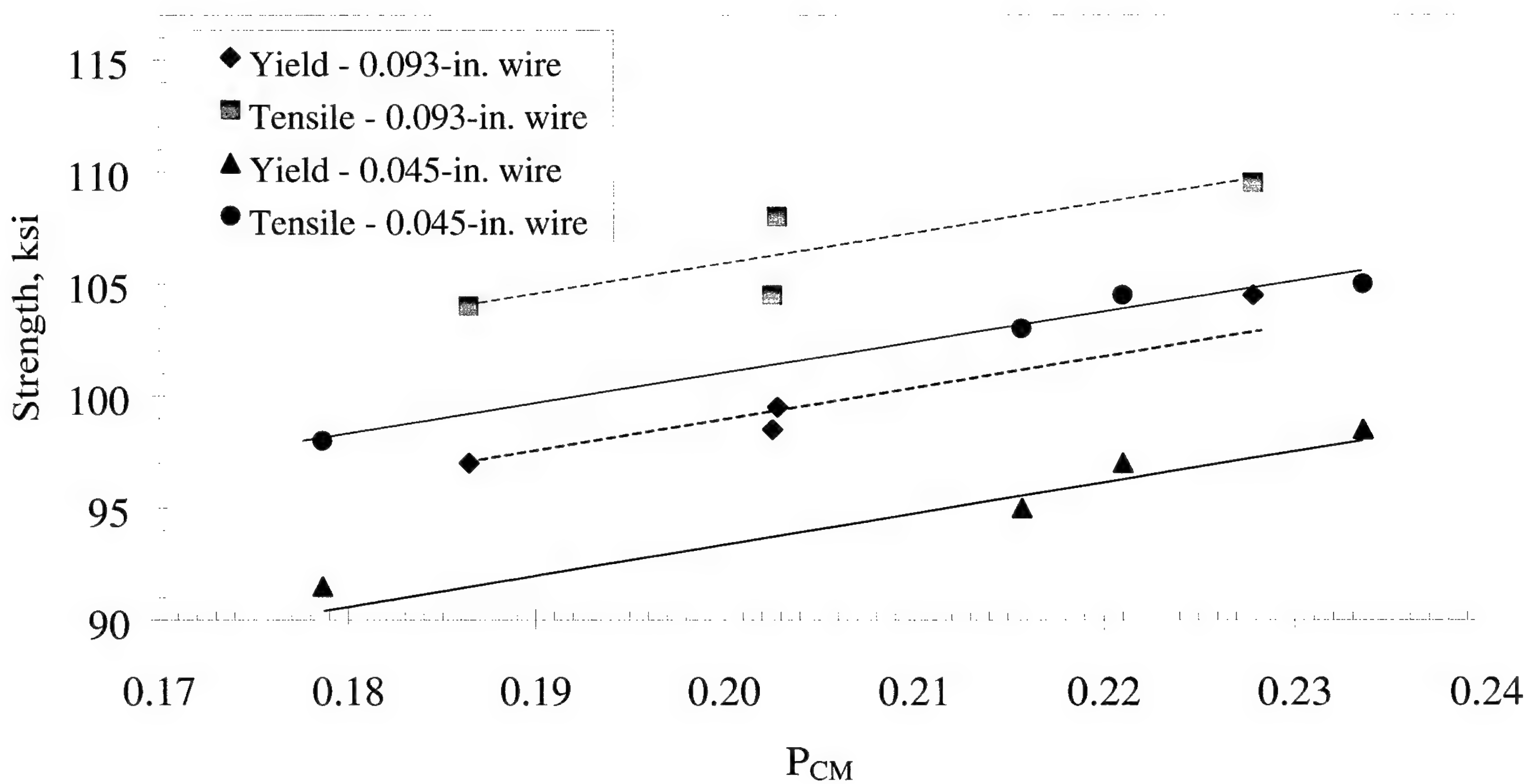

Figure 2b. Weld Metal Strength as a Function of Weld Metal P_{CM} and Wire Size.

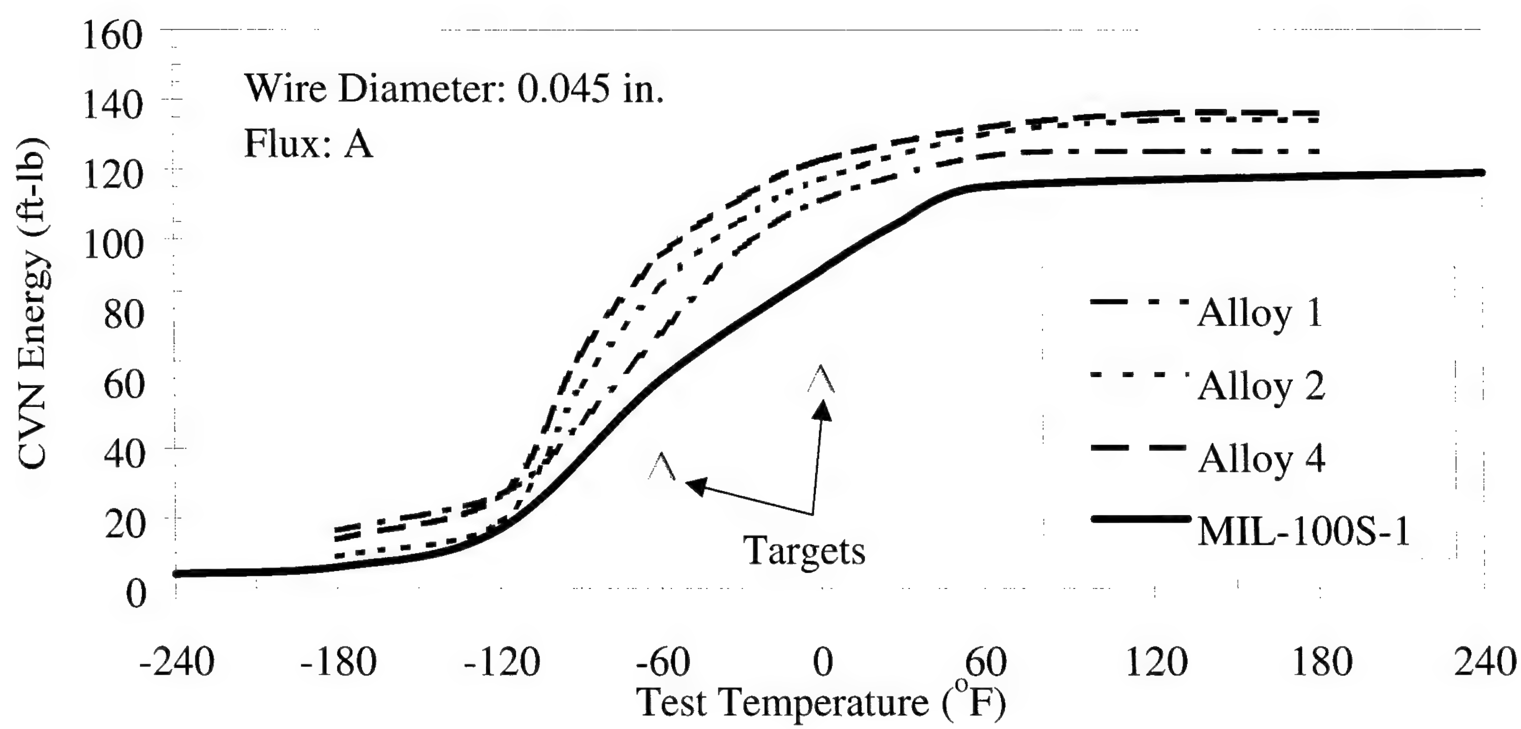

Figure 3. Comparison of CVN Performance for Alloy and MIL-100S-1 Wire Submerged Arc Weld Metals.

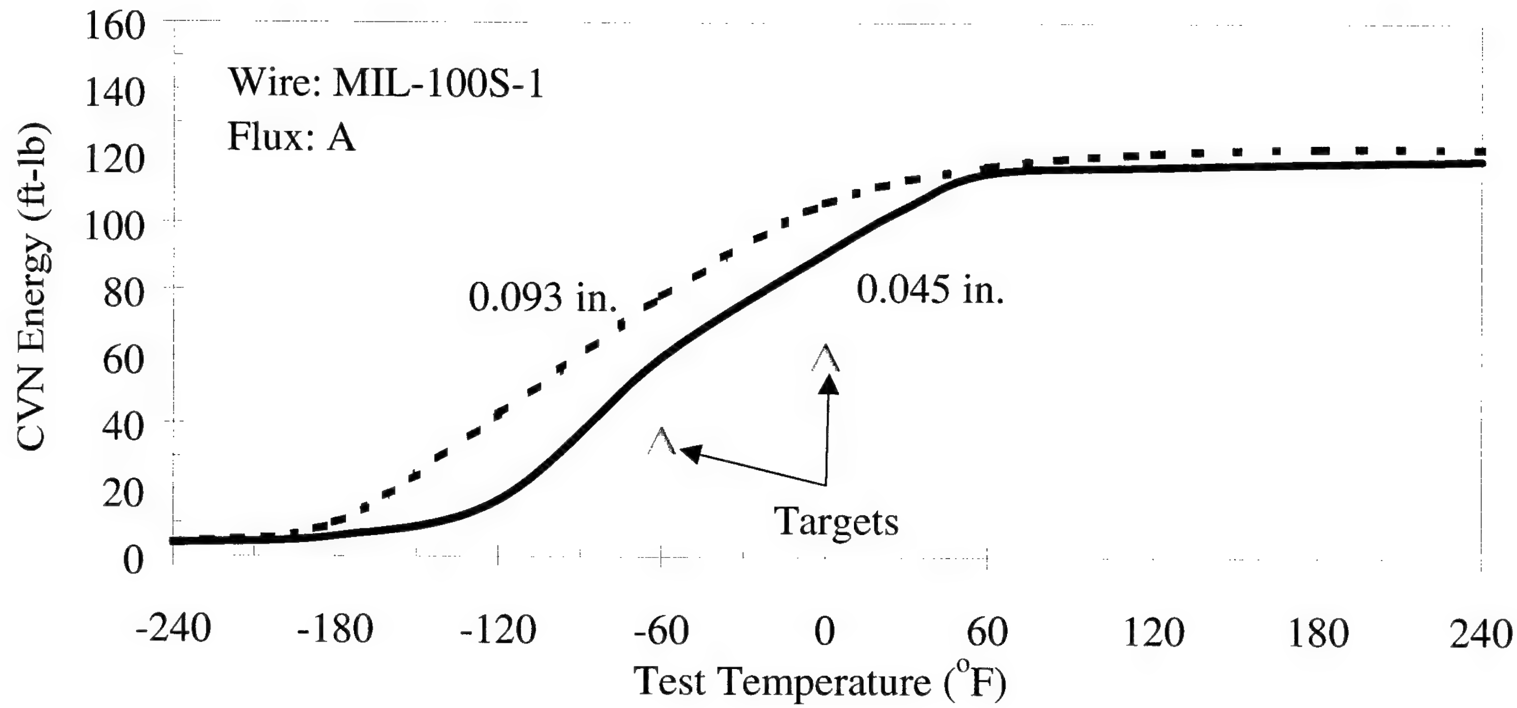

Figure 4. Effect of Wire Size on Weld Metal CVN Performance of MIL-100S-1 Submerged Arc Weld Metals.

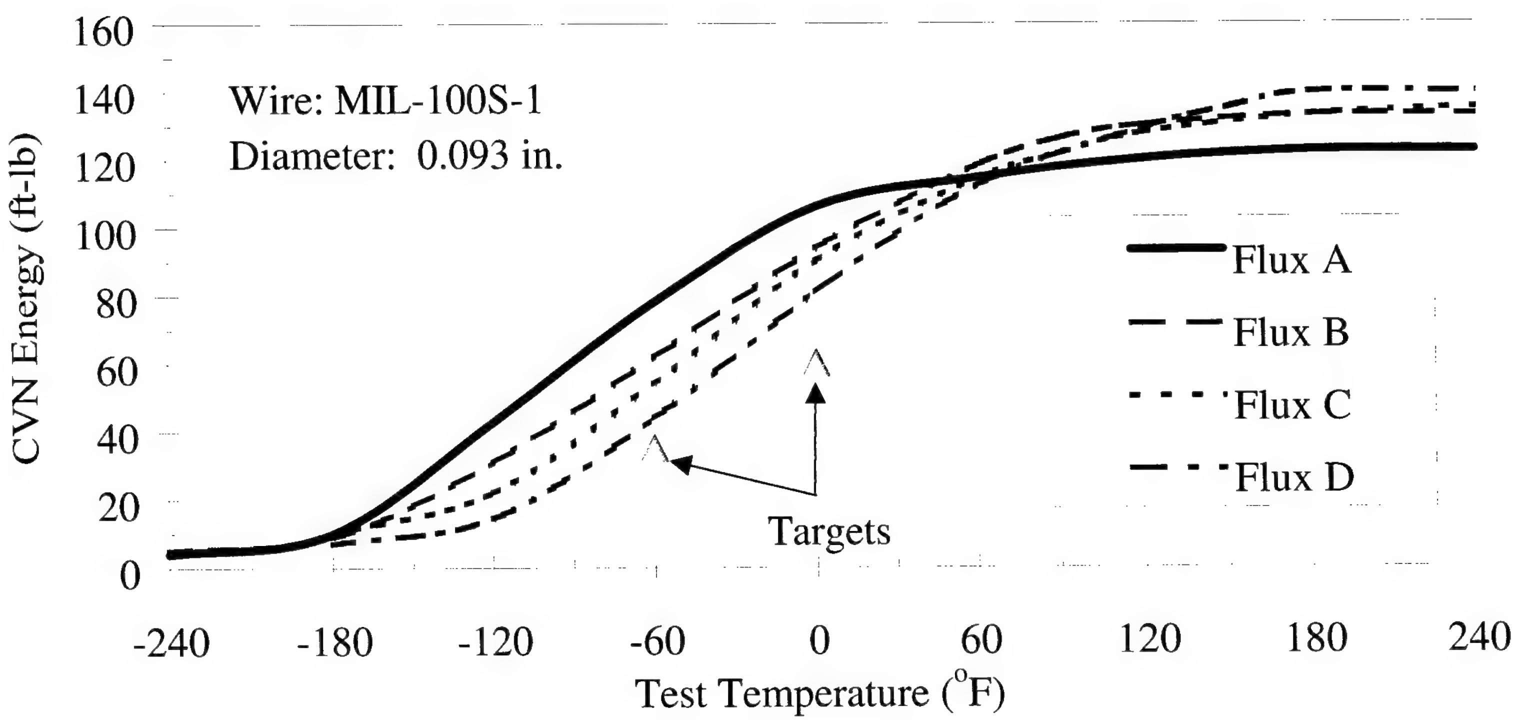

Figure 5. Effect of Flux Composition on Weld Metal CVN Performance of MIL-100S-1 Submerged Arc Weld Metals.

References

1. NAVSEA Technical Publication T9074-AD-GIB-010/1688, "Requirements for Fabrication, Welding, and Inspection of Submarine Structure," 1 May 1997.

2. DeLoach, J.J., "Development of an Improved MIL-100S Wire for Naval Ship Construction," Presentation made at 79th Annual American Welding Society International welding and Fabricating Exposition and Annual Convention, Detroit, Michigan, 26-30 April 1998.

3. Rosenthal, D., "Mathematical Theory of Heat Distribution During Welding and Cutting," *Welding Journal Research Supplement*, Vol. 20, No. 5, pp. 220s – 225s, 1941.

4. Jhaveri, P., W.G. Moffatt, and C.M. Adams, Jr., "The Effect of Plate Thickness and Radiation on Heat Flow in Welding and Cutting," *Welding Journal Research Supplement*, Vol. 41, No. 1, pp. 12s – 16s, 1962.

5. Dorschu, K.E., "Control of Cooling Rates in Steel Weld Metal," *Welding Journal Research Supplement*, Vol. 47, No. 2, pp. 49s – 62s, 1968.

6. DeLoach, J.J., J.M. Blackburn, R.J. Wong, and G.L. Franke, "Development of an Improved MIL-100S Wire for Naval Ship Construction," Proceedings of The Third Pacific Rim International Conference on Advanced Materials and Processing (PRICM 3), Honolulu, Hawaii, The Minerals, Metals, and Materials Society, Edited by M.A. Imam, R. DeNale, S. Hanada, Z. Zhong, and D.N. Lee, Vol.II, pp 2291 – 2296, 12-16 July 1998.

7. Military Specification MIL-E-23765/2C, "Electrodes and Rods – Welding, Bare, Solid, or Alloyed Cored, Low Alloy Steel," 17 June 1983, with Amendment 2, 10 February 1984.

8. Military Specification MIL-S-24645A(SH), "Steel Plate, Sheet, or Coil, Age-Hardening Alloy, Structural, High Yield Strength (HSLA-80 and HSLA-100)," 10 January 1990, with Amendment 1, 24 September 1990.

9. Tuliani, S.S., T. Boniszewski, and N.F. Eaton, "Notch Toughness of Commercial Submerged Arc Weld Metal," *Welding and Metal Fabrication*, Vol. 37, No. 8, pp. 327 - 339, August 1969.

10. Military Specification MIL-E-23765/2E, "Electrodes and Rods – Welding, Bare, Solid, or Alloy Cored; and Fluxes, Low Alloy Steel," 22 April 1994.

11. Krause, G.T., *Heat Flow and Cooling Rates in Submerged-Arc Welding*, M.S. Thesis, The Ohio State University, 1978.

12. Blackburn, J.M., and G.L. Franke, "Consideration of Calculated and Measured Weld Metal Cooling Rates for Welding High Strength Steels," Proceedings of Infrastructure: New Materials and Methods for Repair, American Society of Civil Engineers, November 1994.

13. Ito, Y., and K. Bessyo, "Cracking Parameters of High Strength Steels Related to Heat Affected Zone Cracking, Part 2," *Journal of the Japan Welding Society*, Vol. 37, No. 10, pp. 1134 - 1144, 1969.

Appendix

CVN Transition Curves for Submerged Arc Weldments

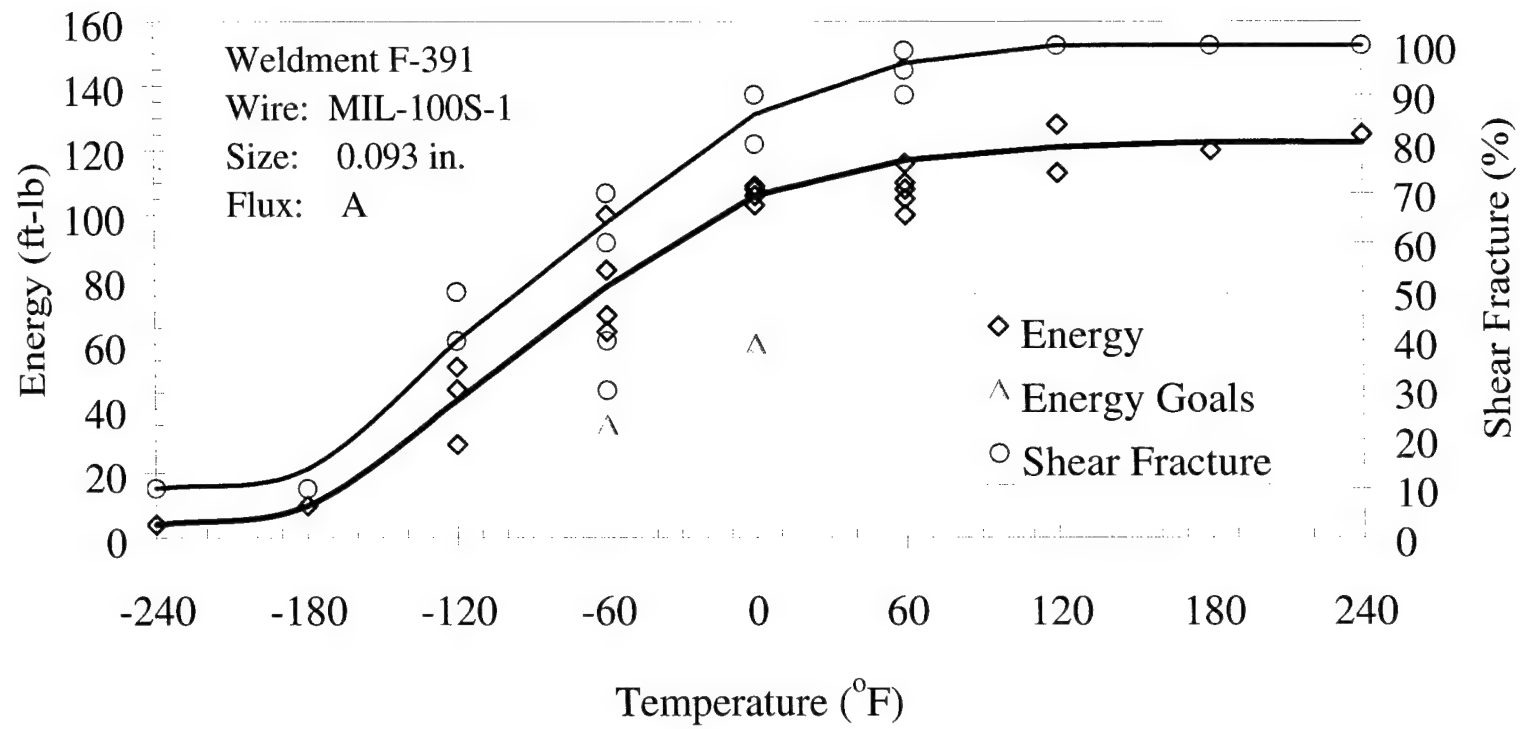

Figure A1. CVN Performance of Weldment F391.

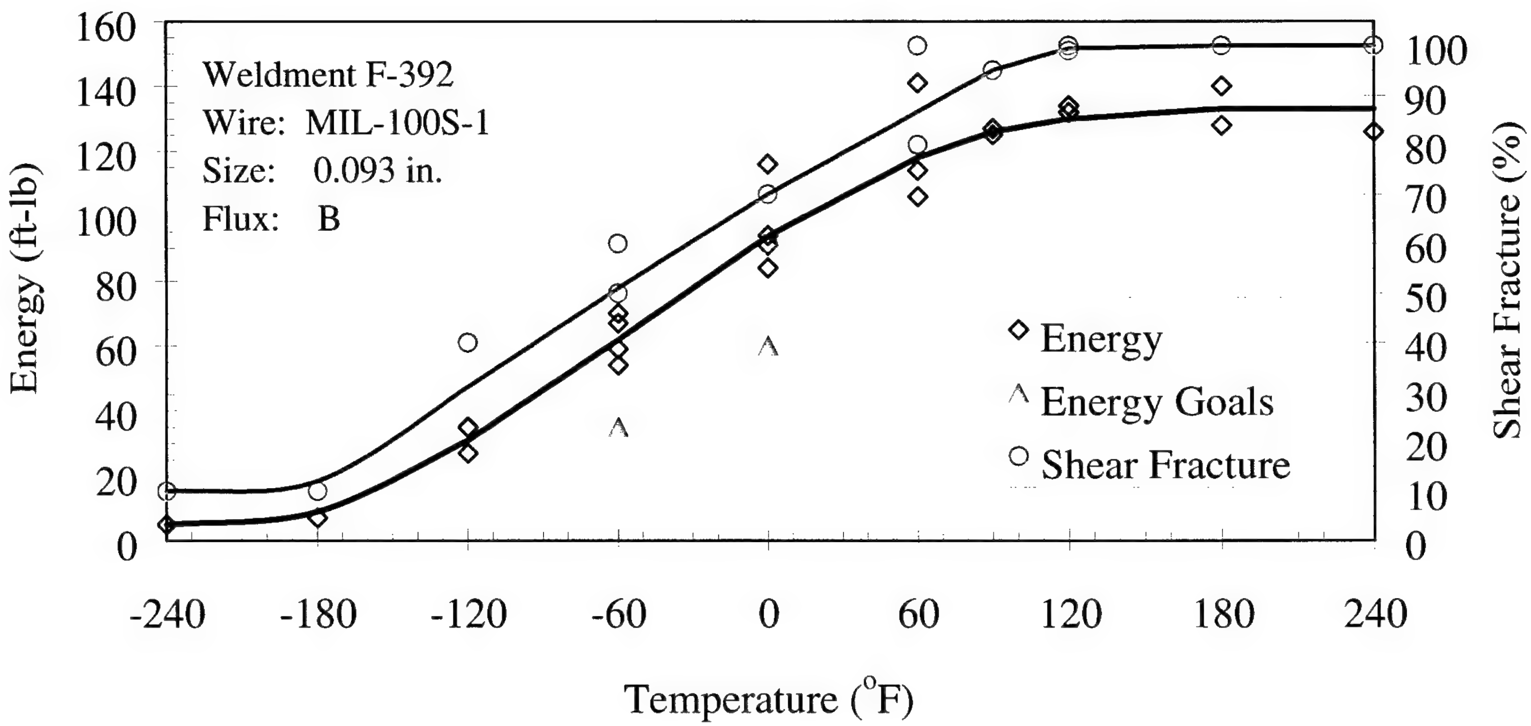

Figure A2. CVN Performance of Weldment F392.

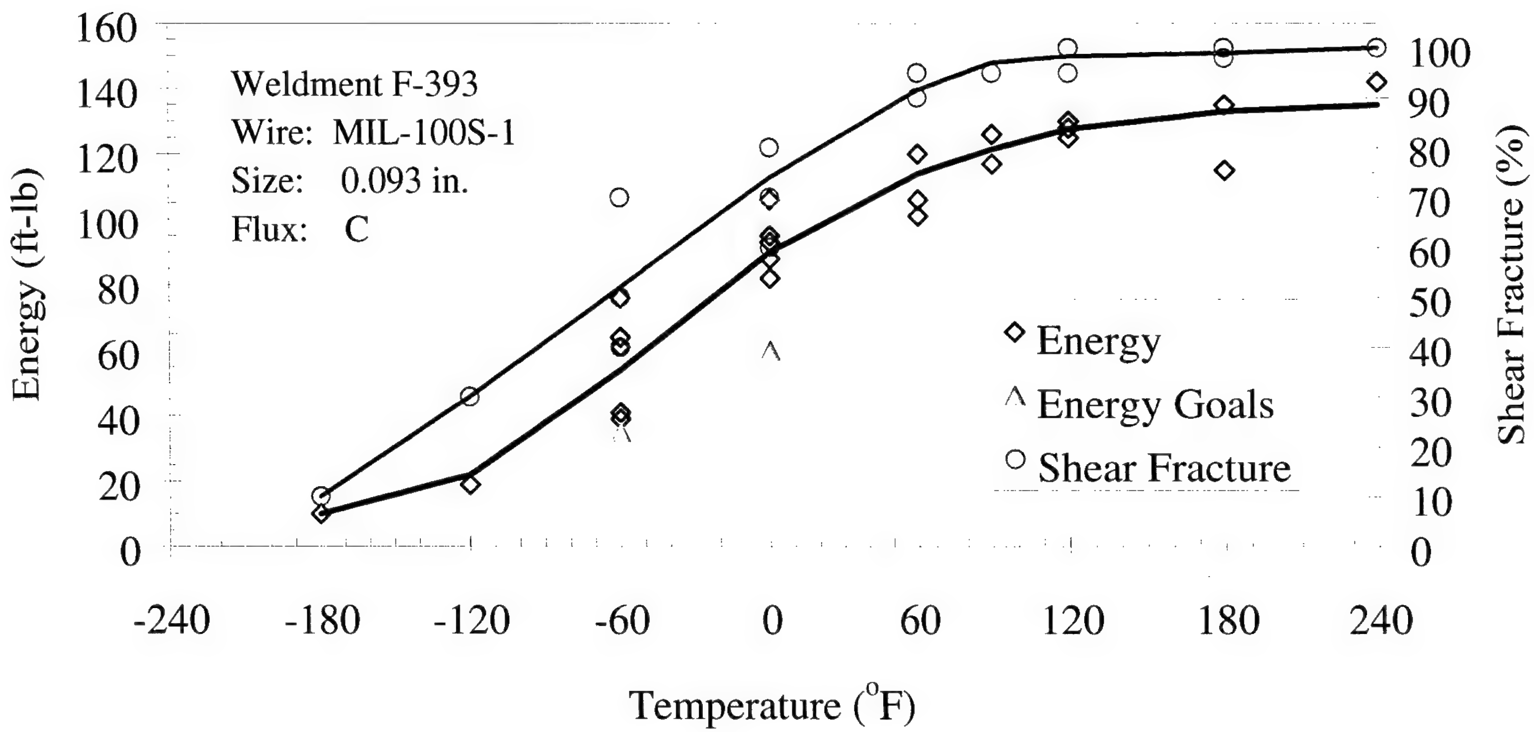

Figure A3. CVN Performance of Weldment F393.

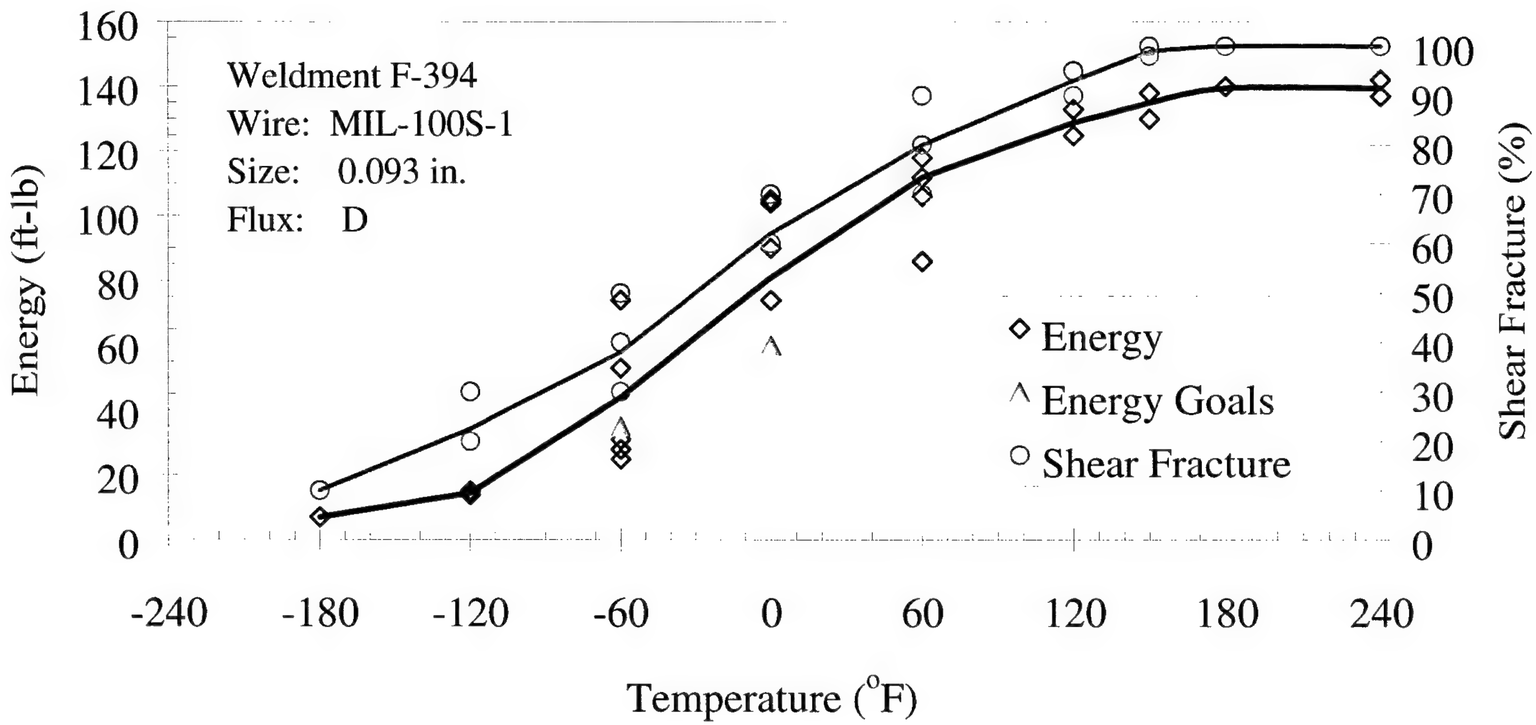

Figure A4. CVN Performance of Weldment F394.

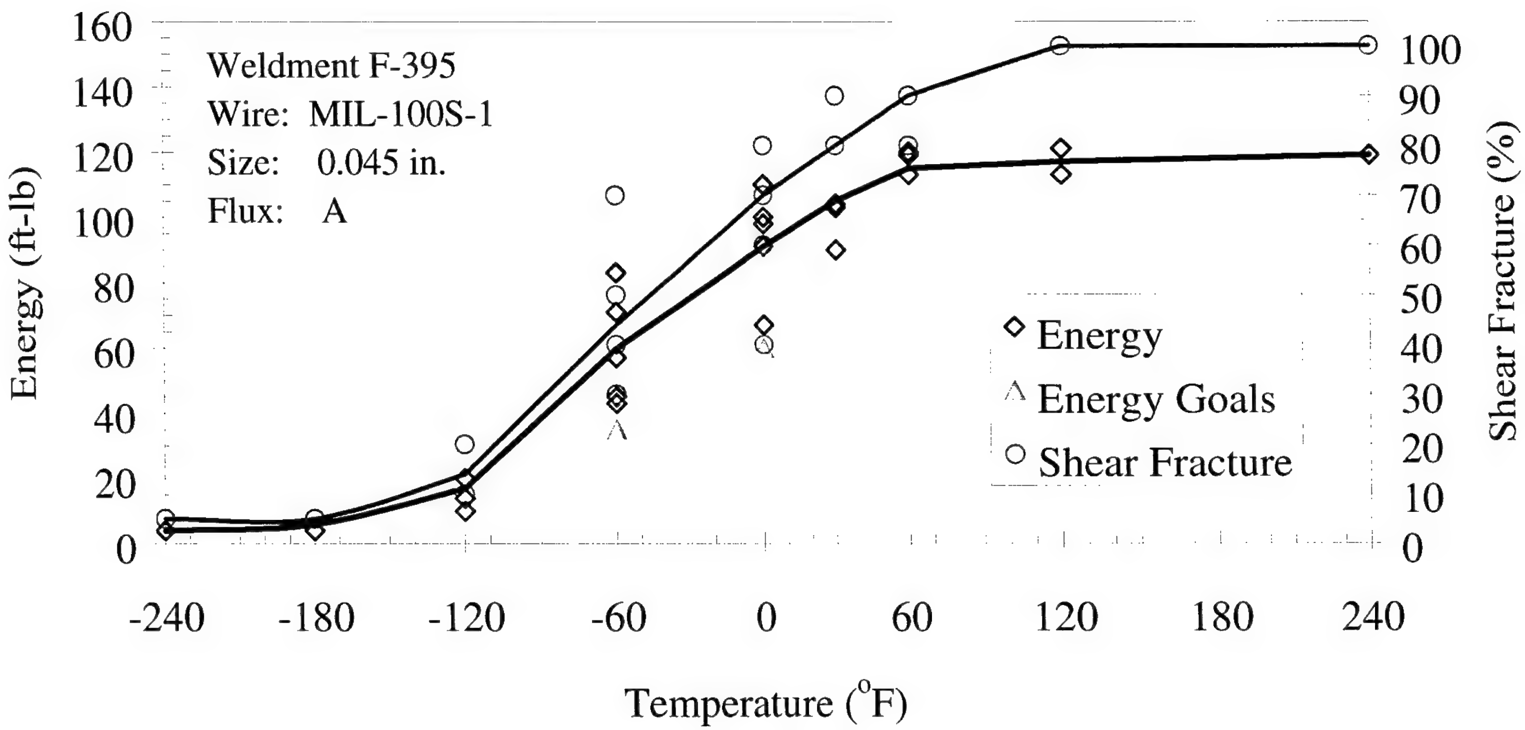

Figure A5. CVN Performance of Weldment F395.

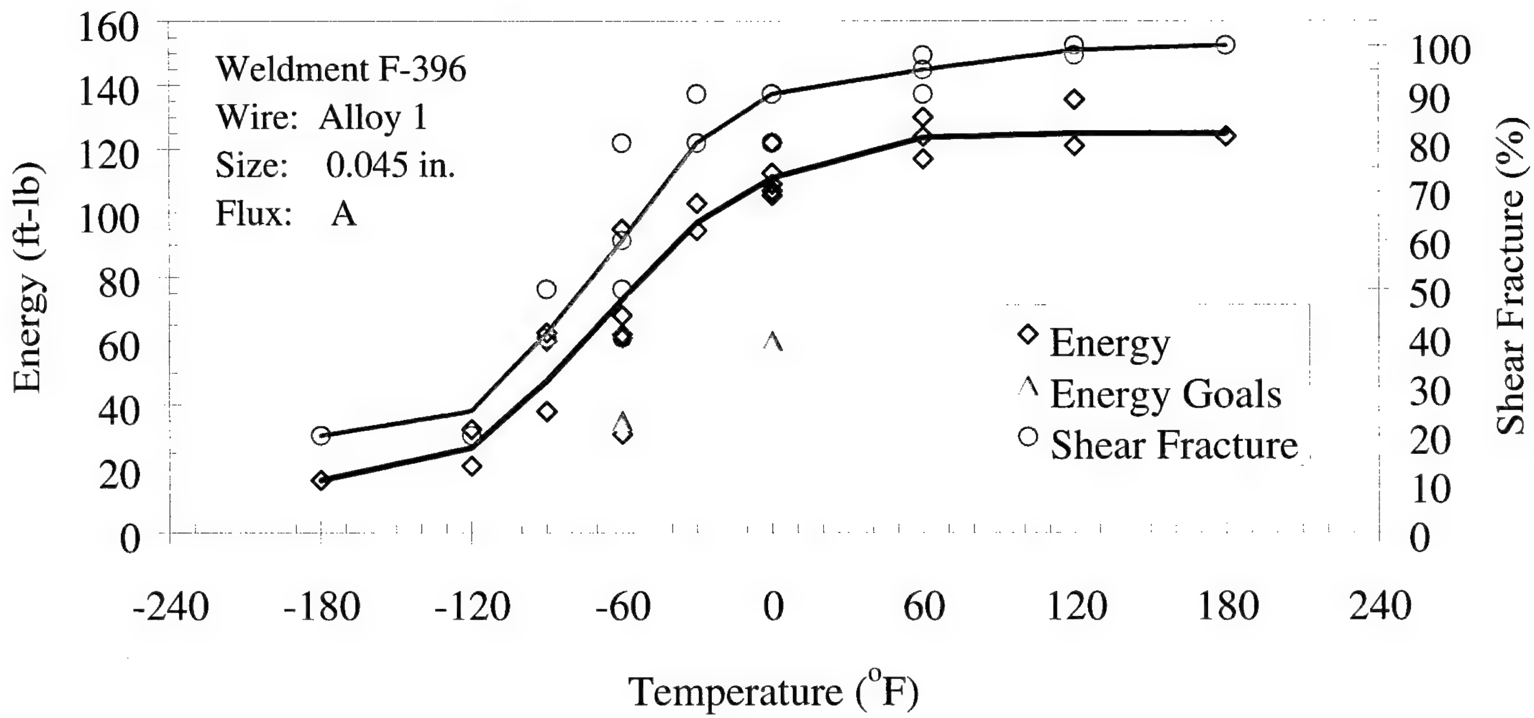

Figure A6. CVN Performance of Weldment F396.

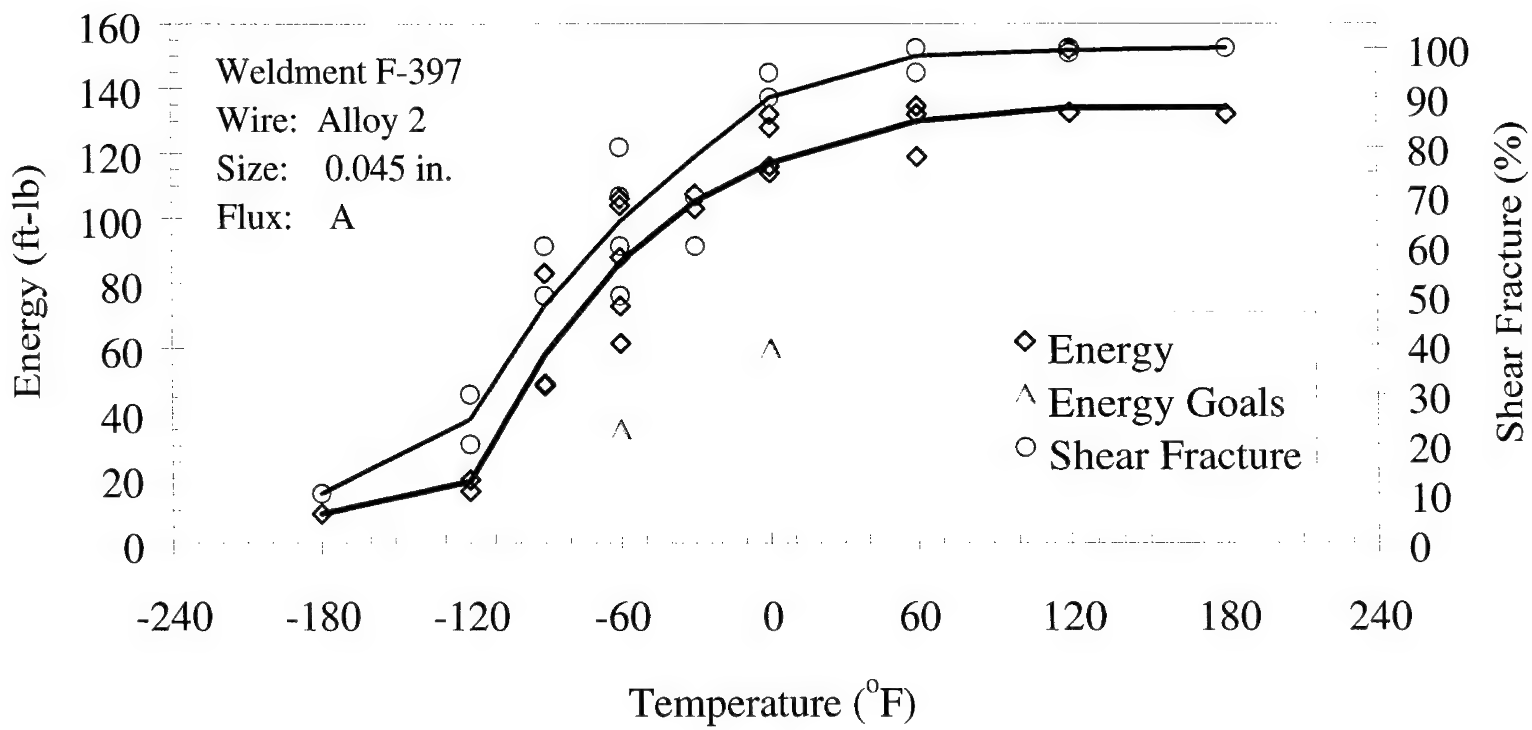

Figure A7. CVN Performance of Weldment F397.

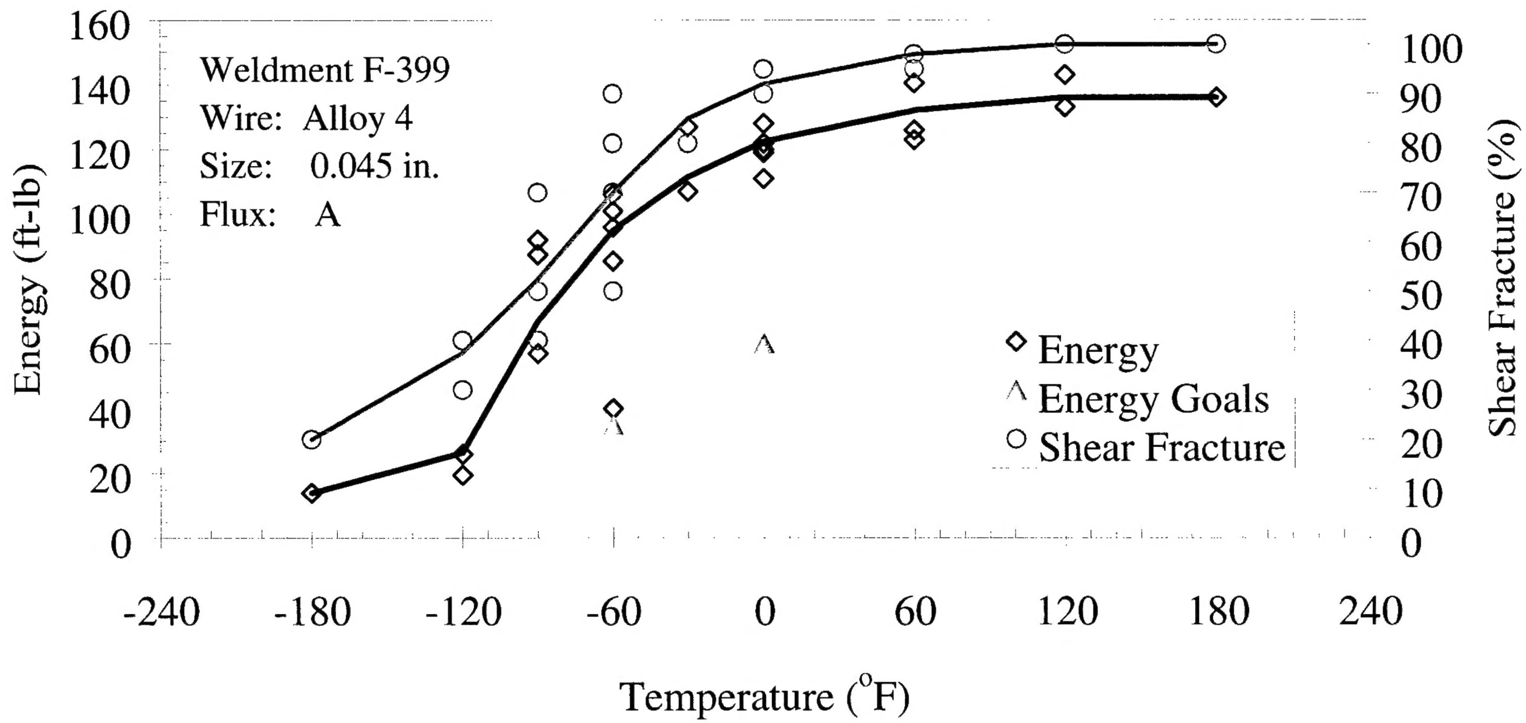

Figure A8. CVN Performance of Weldment F399.

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